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WORKSHOP RESULTS ON SMALL-PERIOD WIGGLER DESIGNS*

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Abstract

In this paper, we present a review of a workshop on small-period wiggler and undulator designs held at Los Alamos National Laboratory on April 13, 1989. The wiggler designs are based on the following mechanisms: microwave fields, electromagnetic coils, miniature permanent magnets, current sheets, superconductive coils, and iron-free pulsed wire.

1. Introduction

The wavelength of the light produced by a free-electron laser (FEL) is proportional to the wiggler (or undulator) period divided by the square of the relativistic gamma of the incident electron beam. As we will be discussing both large and small values of a_w, for simplicity we will use the term wiggler to mean wiggler or undulators. The efficiency of converting the electron-beam energy to light is a function of the peak magnetic field on-axis in the wiggler. Therefore, if small period wigglers with appreciable on-axis magnetic fields can be built, then short-wavelength lasers at a reasonable cost are possible.

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Wiggler technology has slowly advanced in the last six, years. Most of the FELs in existence were built around existing accelerators. Progress has been slow because researchers were more concerned with showing that FELs can be built and operated; thus, advances beyond present wiggler technology were not required. Now that the initial phase of experimental verification of FEL operation has been demonstrated, researchers interested in either going to shorter wavelengths or reducing the electron-beam energy required need shorter period wigglers.

The pulsed-electromagnet approach has the potential for greatly reducing the electron-beam energy required to reach short FEL wavelengths. This type of wiggler was designed by Jack Slater of Math Sciences (but with a 3-cm period). This wiggler was never built because of the advent of samarium cobalt permanent magnets and their superior performance for his particular application (a long period wiggler).

To determine the present status of wiggler technology, the "Workshop on Small-Period Wiggler Designs," was hosted by Los Alamos National Laboratory on April 13, 1989. The following information recorded by John Booske of the University of Maryland, summarizes that workshop.

2. Proceedings

The program began with Klaus Halbach making a few informal observations relevant to short-period wigglers and wigglers in general. First, in considering the issue of permanent-magnet versus electromagnet wigglers, the permanent-magnet wigglers simply scale down in size at fixed field strength (assuming a self-similar scaling of the wiggler gap and other dimensions with the wiggler period). When scaling down electromagnets, the current density has to scale like the inverse of the linear dimensions of the device if one wants to keep the field strength fixed, making cooling more and more difficult as the linear dimensions of a DC device decrease. For that reason, permanent-magnet wigglers give higher fields on-axis than electromagnet wigglers below a period length of about 15 to 20 cm. Here, new developments in soft-iron-type materials would improve the possibilities [1]. Likewise, new developments can be made in permanent-magnet materials with higher remnant fields. In general, superconducting electromagnets will produce the highest fields, especially at the longer wiggler periods. Obviously, permanent wigglers do not require a power supply. There are two possible versions of permanent-magnet wigglers: (1) iron-free and (2) hybrids. Klaus prefers the second option because of the possibilities for higher fields and lower sensitivity to tolerances in permanent-magnet materials. A final, almost rhetorical, challenge was offered regarding the development of short-period wigglers: as the wiggler periods get smaller, how do you accurately measure the three-dimensional structure of the wiggler fields?

The first two formal presentations—one on electromagnetic wave wigglers and the other on small electromagnet wigglers—were by Bruce Danly of MIT. For electromagnetic wigglers, the resonance condition provides an extra factor of 2 in Doppler upshifting compared to magnetostatic wigglers:

$$\lambda_s \approx \frac{\lambda_w(1 + a_w^2)}{2(1 + k_{ws}/k_w)\gamma^2} \approx \frac{\lambda_w}{2(1 + k_{ws}/k_w)\gamma^2} .$$

When millimeter-wave gyrotrons are used as the pump, one can use either high-Q cavities with standing-wave wigglers or possibly a ring resonator with a traveling-wave wiggler [2]. The former is probably easier to realize in a practical configuration but faces potential problems of higher wall loadings and more complicated electron orbits (due to the forward and backward waves of the standing pattern). The complex orbits will likely result in broader-gain spectra and higher harmonics than for traveling waves when a_w is large. This analysis is supported by spontaneous emission spectra calculations [3]. For example, when $a_w \leq 0.5$, typically only the two lowest order FEL resonances (a high-frequency one with the backwards wave and a very low-frequency one with the forwards wave) have gain. Presumably, some method for selective feedback would be required because the low-frequency mode gain always equals or exceeds the gain in the desired high-frequency interaction. At large relative values of axial wiggler wave number, $k_{wz}/k_w > 0.9$, the gain spectrum is rich in all sorts of harmonics and one might expect mode competition problems. As mentioned above, this problem is exacerbated at large values of a_w.

In addition, superconducting cavities could provide much higher Q-values and, thus, larger values of a_w for the same wiggler power. Unfortunately, technological thermal limitations would appear to constrain $a_w < 0.01$ in superconducting cavities with $\lambda_w \leq 5$ mm unless advanced cooling techniques are incorporated into the cavity design. Much more complex thermal and materials engineering solutions would be required to alleviate some of this restriction. A design based on a copper cavity indicated that for $\lambda_w \approx 10$ mm (30 GHz), one could achieve $a_w \approx 0.1$ to 0.2 with 1 to 10 MW of cavity power. Finally, results were presented from a completed experiment using a gyrotron (~140 GHz; $V_b = 65$ kV, $I_b = 5$ A) and a wiggler cavity with a Q-value $\approx$20 000. For this case, a value of $a_w \approx 0.008$ was achieved for $k_{wz}/k_w = 0.9$ [5]. In a planned second experiment, an order-of-magnitude increase in a_w is expected because a higher power gyrotron will be used.

The second talk (also presented by Danly) discussed work by S. C. Chen and coworkers at MIT or "tunable" microwiggler [4] electromagnets achieved by using magnetic structures with many turns of very fine wire wrapped around the C-shaped, Fe-Si cores. A small cross-section beam would be propagated down the gap in the one arm of the core. With this configuration, it is possible with careful practice to tune currents in the individual core windings to get the desired $B_w(z)$ profile. Typical designs call for 100 to 1000 turns per core. Prototype experiments for a wiggler period of 2.4 mm, 10 A/core (3200-A turns/period), and a gap-to-period ratio of 1.2 gives peak fields of ~0.6 kG. An improved design with 800 turns per core (40 000-A turns/period), wiggler period of 5.0 mm, and a gap-to-period ratio of 0.5 gives peak fields of ~3.2 kG. To achieve peak fields near 3 kG in these wigglers, it is necessary to restrict operation to pulsed mode or to employ a 4K superconducting configuration. The restricted operation avoids melting of the fine wires used in the wiggler windings.

The next talk by Bob Jackson of the Naval Research Laboratory described a Reduced Edge Effect Linear (REEL) Wiggler. Similar to work in progress at the University of Maryland (UM), the motivation for Jackson's wiggler development was based on a need for cheap, quick fabrication and simple flexibility to vary the field intensity in laboratory FEL/ubitron experiments. With an initial interest in a_w values near 0.2 to 1.0 for periods of 1.0 to 3.0 cm, the cost and ease of varying a_w led to a selection of electronic, rather than permanent-magnet wigglers. Starting with the single-layer University of Maryland "current sheet" wiggler, Jackson showed how using multiple layers connected in series reduces or eliminates uncompensated "virtual bias currents" at the wiggler sides while simultaneously reducing excess field end effects. Theoretically, this configuration predicts that DC operation might yield slightly higher fields than AC operation (the trade-offs here are between AC skin-depth shielding of leakage flux and eddy current losses). Measurements on a 3-cm period prototype indicated very good agreement with theoretical design calculations. In the prototype, side-teeth were added to the soft-iron cores to provide wiggler-plane focusing for the electron beam. However, the REEL design's is improved performance over the original (University of Maryland) single-layer design is less dramatic if the iron becomes saturated. The use of permanent magnets in a "hybrid" configuration alleviates some of the saturation problems, although such a configuration may be more difficult to fabricate on a microwiggler scale size (ℓ_w < 1.0 cm). Methods for fabricating microwiggler structures with high uniformity were discussed (i.e., milling accuracies, wire-EDM, solid-state fabrication techniques, etc.). Finally, scaling arguments along with fabrication method considerations indicate that for periods down to 1 mm or shorter, peak fields comparable to permanent-magnet wigglers (i.e., ~2 to 4 kG in the gap) are likely. A critical issue for these small dimensions, of course, is the feasibility of maintaining a thermally stable structure, especially for DC operation.

Peter Walstrom of Grumman Space Systems Division (at Los Alamos National Laboratory) described a numerical design and scaling study for superconducting wigglers, including holmium inserts. Short-sample critical-current performance of the best available NbTi composite wire indicated that the maximum feasible current density in the windings is probably around 10^5 A/cm^2. Present capability would be confidently compatible with current densities up to 7.5×10^4 A/cm^2. Two mechanical assemblies might be considered. An assembly with potted windings would be easier for assembly and mechanical support but would require indirect cooling. An unpotted assembly, on the other hand, would allow for direct wetting with liquid helium and thus be more thermally stable. At 10^5 A/cm^2, field values in the windings approach 2.25 T for an air-core and 3.5 T for a holmium core wiggler. In either case, this is less than the 4.3 T critical fields for 10^5 A/cm^2 with NbTi superconductor. Using numerical simulation, characteristics of various designs were investigated. The gap fields were shown to observe the standard $B_w \propto 1/[\sinh(k_w\delta)]$ scaling where δ is the wiggler gap and $k_w = 2\pi/\ell_w$. As an example of achievable design, for a 1.5-cm wiggler period magnet with a winding current density of 75 000 A/cm^2 and a 6-mm gap, a peak gap field of 0.7 T is obtained with an aircore, while 1.15 T is obtained with the holmium core inserts. Similarly, for $\ell_w = 1.0$ cm,

$\delta = 4$ mm, and jav $= 75\,000$ A/cm2, a gap value of $a_w = 1.06$ ($B_w = 1.14$ T) is predicted. Mechanical design of superconducting wigglers must take into account a cold beam tube, consideration of thermal expansion and contraction issues, and the amount of gap spacing left after allowing for beam-tube wall thickness compared to the desired beam dimensions. Superconducting short-period wigglers might be ideally suited to storage ring undulator applications.

Motivated by an interest in all types of permanent and electromagnet wigglers, Jack Slater of Spectra Technology presented some scaling considerations, comparing the simplest permanent-magnet configuration to the simplest (superconducting) electromagnet configuration. As he pointed out, improvements on these most basic configurations generally yield field enhancements in the order of tens of percent and, thus, do not change the basic comparison picture. The wiggler parameter for a permanent magnet typically scales as

$$a_w^{rms} \approx 10^{-4} B_w(\mathrm{G}) \ell_w(cm)\, e^{-n\delta/\ell w}$$

while the scaling for the electromagnet wiggler is roughly

$$a_w^{rms} \approx 10^{-5} J(\mathrm{A}/cm^2)\, \ell_w^2\,(cm) e^{-n\delta/\ell w} \quad ,$$

where δ is the magnet gap.

Slater also described an optimized electromagnet scaling analysis assuming that the radiation frequency and wiggler gap are held fixed while allowing the wiggler period and beam energy to vary. It was also assumed that the wigglers were tapered, for which the taper was in all cases adjusted for maximum extraction at fixed gain.

Under these conditions, a_w remains relatively constant as a function of winding current density due to an increase in B_w that offsets a decrease in ℓ_w as J is increased. Along with any reduction in ℓ_w, however, there must be a reduction in beam emittance to maintain constant equivalent energy spread in the nonuniform gap fields. An important scaling question arises: Can permanent-magnet or electromagnet (superconducting) wigglers yield the higher values of a_w for short wiggler periods? Because of constraints on remnant field in the permanent magnet versus limits on the current density in electromagnets, one finds a cross-over wiggler period of approximately 1 cm for current densities on the order of 10^5 A/cm^2. For $\ell_w \geq \sim 1$ cm, electromagnets yield higher values of a_w, while for $\ell_w \leq \sim 1$ cm, permanent wigglers yield the higher fields. The crossover wiggler period naturally decreases with increasing maximum current densities. This might leave open the possibility that pulsed, high-peak-current electromagnet wigglers could extend the range of electromagnet preference down to somewhat smaller wiggler periods for pulsed applications. Ultimately, the permanent wigglers probably win out for extremely short periods ($\ell_w < 1$ mm), however, achieving an a_w close to unity is not possible without the development of new materials. Finally, one should also consider mechanical stresses and whether self-magnetic fields exceed critical values when designing superconducting wigglers.

John Booske of the University of Maryland discussed current sheet electromagnet wigglers developed at the University of Maryland to support a university research development program in high-average-power millimeter-wave FELs. Similar to Jackson's earlier comments, the need here was for cheap, simple fabrication and easily varied wiggler fields of 1 to 2 kG for $\ell_w \approx 0.5$ to 1.5 cm—hence, again the electromagnet was chosen. A shortcoming of these electromagnet wigglers, which utilize soft-iron cores to enhance the wiggler gap fields, is that they are generally not compatible with axial beam guide fields. However, the Maryland experiment employs sheet beams that are unstable in axial fields and only compatible with pure wiggler focusing. Early measurements on 3 to 10-mm period wigglers demonstrated that producing the desired field strengths was probably straightforward enough, but more serious questions remained on uniformity as well as end effects, which deleteriously affect beam transport. Both theory and experimental evidence were presented indicating that some field enhancement is possible by reducing leakage flux in the copper meander path, as well as by using very thin iron laminations to reduce eddy current losses in the cores. A systematic study has been underway to identify those aspects of the wiggler fabrication that most sensitively affect wiggler field uniformity. Specifically, early wigglers were constructed by bending copper foil into a meander path with laminations inserted in between. More recent versions were made by precision machining the copper conductor and packing the iron laminations into epoxied cores. Recent measurements suggest that the iron core fabrication and alignment may be the most important issue in obtaining highly uniform wiggler fields. For example, in a 1-cm period wiggler, initial assembly without critical attention to core selection or alignment relative to gap yielded wiggler fields with $\pm 10\%$ to 20% errors. Reassembling the same magnet after selecting cores of more uniform thickness and aligning the cores along the gap with a precision-milled spacer bar yielded field errors of less than $\pm 2\%$. This decrease in field errors was accomplished with cores having a thickness uniformity within 4% of average and a gap alignment accuracy of approximately $\pm 0.5\%$ to 1.0%. A critical aspect of Maryland's FEL effort involves whether wiggler-focused sheet beams can be transported down the narrow gaps between short-period wigglers without beam interception on the walls. Thus, there has been considerable effort to test their wigglers in actual beam propagation experiments. First, the researchers have found that a quick up-taper of the wiggler field over 1/2 to 1 periods is necessary and sufficient to maintain wiggler focusing without inducing wiggle plane drift. This field tapering, as well as improved field uniformity, was achieved by hand adjustment of the gap spacing on individual iron cores and sometimes the additional use of magnetic shorts at the wiggler edges to shunt excess flux around the gap. Future plans call for incorporation of the REEL wiggler modification described by Jackson, as well as fabrication of the cores into a single laminated "comb-like" structure with the laminations oriented along the wiggler axis, rather than transverse to it. Finally, future studies will investigate methods of focusing beam "edge-halo" electrons in the wiggle plane without tapering the pole pieces near the gap.

Art Toor of Livermore described the feasibility of fabricating long ($N_w \approx 10^4$) permanent-magnet wigglers with very short periods ($\ell_w \approx 100\ \mu m$) for the generation of wiggler-induced x-rays with electron beams [9]. Results were achieved with permanent magnets down to 0.7-mm wiggler periods. At shorter periods, handling of the small scale structures became rather difficult. Two configurations were investigated: one involved machining a solid block of permanent-magnet material with uniformly oriented polarization, which was then magnetized and immersed in a reverse bias field; the other used individual "foil-like" magnets with alternating polarity in the classic wiggler configuration. For the second "laminar foil" wiggler, the wafers were produced by slicing sections from a solid, unmagnetized block. In this case, diamond sawing produced better uniformity in magnetized wafers than lapping produced. Generally, $SmCo_5$ magnets performed better than NdFe (B) magnets, especially for wafer thickness less than 1 mm. A special (expensive) nickel-plating process indicated that much of the improve SmCo performance was due to oxide formation on the NdFe (B) magnets. Similar results were also observed with the bias field wiggler configuration. Fabrication difficulties occurred for very thin wafers; at thicknesses much less than 0.25 mm, the wafers curled up like potato chips because of internal stresses in the material. Random field variations between individual wafers made it absolutely necessary to individually characterize each wafer in the laminar foil configuration. As with permanent-magnet wigglers, field errors are unacceptable when the wafers are randomly selected. The ratio of accepted to rejected wafers decreases rapidly with decreasing wafer thicknesses, e.g., 0.9 at 800 μm, 0.4 at 500 μm and 0.2 at 150 μm. Several prototypical microwigglers were fabricated and tested including bias-field wigglers with periods 62 to 700 μm, N_w = 32 to 250 periods (all using NdFe-B) and laminar foil wigglers with ℓ_w = 250 to 1000 μm, and N_w = 50 to 250 periods (both NdFe-B and SmCo). For gap-to-period ratios of ~0.5, gap fields of 1 to 3 kG were observed. Generally the bias-field configuration produced more uniform fields and was easier to fabricate and assemble although the fields were obviously reduced by two from the maximum possible; also the bias magnet introduced considerable mass and a need for cooling or low duty factor pulsing to the configuration. The laminar foil magnet required no bias field (and thus no liquid nitrogen) and thus could be remotely positioned in an actual application. On the other hand, the large number of wafers and difficulties in controlling uniformity would appear to constrain the laminar foil configuration to wigglers with periods greater than 250 μm.

The final paper, presented by Roger Warren of Los Alamos National Laboratory, described a program to investigate pulsed wire wigglers for short-pulse RF linac FELs. Starting out with a scaling argument in which he fixed beam current, beam energy, k_w, and N_w, one finds wiggler designs at short periods that maintain high fixed gain, constant gap-periods, ratios, etc. Difficulties with this down-scaling are that for shorter periods one requires improved emittance (to keep fixed axial energy spread and/or to avoid wall interception within the small gaps), more precise fabrication techniques, and a wiggler field that increases at short periods (to maintain fixed k_w). Limits to maximum B_w are fixed by the remnant field in permanent wigglers, and the current in wire wigglers (I $\leq$ 10 kA for ℓ_w ~ 1 to 3 mm to avoid coil heating or explosion). Although his own approach was to study helical wire windings, Warren acknowledged an early planar wire wiggler design by Slater, then of Math Sciences. For a design study, several 10-kA examples were considered in which the wiggler periods were 27, 9, 6, 3, 2, and 1 mm, respectively. To achieve a_w near unity, in the absence of any active cooling, it was estimated that temperature excursion limits probably would constrain the minimum wiggler period to ≥ 3 mm when run with >100-μs pulses. With active cooling and/or shorter pulses (1 to 10 μs), one could possibly get down to $\ell_w \leq 1$ to 3 mm at which point hoop stresses become the limiting factor. It was noted that in energizing the wiggler, one may need to tailor the current pulse temporally to compensate for skin and proximity effects. Pre-cooling the wigglers (with liquid nitrogen, for example) does not seem to buy much advantage for the expended effort at these currents and pulse lengths. It did look possible to cool the wigglers actively with a hollow tube soldered to the helical current conductor. On a short time scale, this cooling will have no impact but could help considerably in increasing the maximum duty cycle by dissipating the average heat load between pulses. Finally, a proposed configuration was presented for fabricating a precise wiggler by wrapping a copper wire on an etchable mandrel, potting the wiggler in porous fiberglass, and then etching away the mandrel. Present lead-screw fabrication capabilities appear sufficient for making the mandrel with the necessary precision.

3. Conclusions

At the end of the day's presentations, a round-table discussion was held. A general consensus was reached on guidelines for choosing various wiggler technologies. For $\ell_w > 1$ cm, several options exist. Permanent-magnet wigglers may be more expensive initially and time consuming, but, after initial investment, there are no later costs for power supplies or maintenance. Furthermore, without iron components, permanent-magnet wigglers are compatible with additional axial guide fields. Electromagnets may be easier and less expensive initially, but will continue to consume electrical power and may require cooling. They generally employ soft-iron materials and are not compatible with axial guide fields. Without the soft iron, the fields are weaker and thus more relevant to longer periods and/or very low voltage ubitrons. They are easily tunable in field strength, however, and therefore are a good choice for modestly funded laboratory research. For the absolutely highest magnetic fields with $\ell_w > 1$ cm, superconducting wigglers would be the preferred technology. Obviously, they will require both up-front investment in cost, design, and fabrication, as well as continuous consumption of cryogenics and electrical power.

For $\ell_w < 1$ cm, the choices are somewhat limited. If values of $a_w \sim 1$ are required, then the only likely candidate is a pulsed wire wiggler, which obviously is constrained to pulsed operation. The minimum wiggler period for this technology is probably around 1 mm for pulse lengths between 1 to 10 μs. Values of $a_w \sim 1$ for $\ell_w \approx$ 1 cm are possible with superconducting wigglers. If more modest values of a_w are acceptable at $\ell_w \leq 1$ cm (i.e., $a_w \sim 0.1$ to 0.3 cm), then one can choose between the flexibility and lower initial cost of electromagnets or the ultimately cheaper (but initially more expensive) and somewhat less flexible permanent wiggler. Perhaps the advantages of both technologies are realized in hybrid electromagnet/permanent-magnet wigglers. Finally, it is not clear whether the small clearances, fabrication difficulties, low-field values, and/or high-energy densities prohibit the practical development of magnetostatic wigglers with periods ≤ 1 mm. If so, then the only possible technology for achieving such very short period wigglers—if that is desirable—may be the electromagnetic wiggler described by Danly.

This paper summarizes only the work presented at the workshop and does not include all of the on-going work in the field. If interest in this type of workshop is sufficiently large, future workshops will be held.

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